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Feasibility evaluation of a new irradiation technique: three-dimensional unicursal irradiation with the Vero4DRT (MHI-TM2000)

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The Vero4DRT (MHI-TM2000) is a newly designed unique image-guided radiotherapy system consisting of an O-ring gantry. This system can realize a new irradiation technique in which both the gantry head and O-ring continuously and simultaneously rotate around the inner circumference of the O-ring and the vertical axis of the O-ring, respectively, during irradiation. This technique creates three-dimensional (3D) rotational dynamic conformal arc irradiation, which we term ‘3D unicursal irradiation’. The aim of this study was to present the concept and to estimate feasibility and potential advantages of the new irradiation technique. Collision maps were developed for the technique and a 3D unicursal plan was experimentally created in reference to the collision map for a pancreatic cancer case. Thereafter, dosimetric comparisons among the 3D unicursal, a two-dimensionally rotational dynamic conformal arc irradiation (2D-DCART), and an intensity-modulated radiation therapy (IMRT) plan were conducted. Dose volume data of the 3D unicursal plan were comparable or improved compared to those of the 2D-DCART and IMRT plans with respect to both the target and the organs at risk. The expected monitor unit (MU) number for the 3D unicursal plan was only 7% higher and 22.1% lower than the MUs for the 2D-DCART plan and IMRT plan, respectively. It is expected that the 3D unicursal irradiation technique has potential advantages in both treatment time and dose distribution, which should be validated under various conditions with a future version of the Vero4DRT fully implemented the function.

Keywords: three-dimensional unicursal irradiation; dynamic conformal arc irradiation; image-guided radiotherapy; new irradiation technique; dynamic wave arc irradiation

INTRODUCTION

As the importance and clinical applications of image-guided approaches in external-beam radiotherapy have increased dramatically in recent years, several dedicated machines for image-guided radiotherapy (IGRT) have been developed based on conventional machines or using specially designed systems [1–3]. We have developed a new IGRT system, the Mitsubishi Heavy Industries Ltd (MHI)-TM series, in conjunction with Mitsubishi Heavy Industries Ltd (Tokyo, Japan) and the Institute of Biomedical Research and Innovation (Kobe, Japan) [4]. Currently, this system is

commercially available as the Vero4DRT (Mitsubishi Heavy Industries, Ltd Tokyo, Japan).

The Vero4DRT has a unique configuration. A 6-megavolt (MV) ultra-compact and lightweight C-band linear accelerator is mounted on the gimbals with a multileaf collimator (MLC). The entire X-ray head unit is installed on a rigid O-ring gantry and is designed to rotate 360 degrees along the inner surface of the O-ring (Fig. 1) [4]. Additionally, the O-ring gantry itself can rotate around the vertical axis of the O-ring, which can realize non-coplanar irradiation without rotating the patient couch (Fig. 2). One of the most unique features of this IGRT unit is the capability for dynamic

tracking irradiation using a gimbaled X-ray head; this function is currently under development [5, 6].

In Japan, we are very familiar with two-dimensionally rotational dynamic conformal arc irradiation (2D-DCART) and have a long history of clinical applications using this technique [7–10]. In the initial phase of developing this IGRT system, we did not consider rotating both the X-ray head unit along the inner surface of the O-ring and the O-ring gantry around the vertical axis of the O-ring simultaneously. However, in 2006, to maximize the unique features of this system, we developed the idea of a new irradiation technique in which both the radiation head unit and the ring-shaped gantry rotate simultaneously during dynamic conformal arc irradiation. This technique gives three-dimensional (3D) rotational dynamic conformal arc irradiation, which we term ‘3D unicursal irradiation’. At the

time, we could not conduct a dosimetric study to estimate the advantages of this technique because there were no radiotherapy treatment planning systems (RTPSs) compatible with the Vero4DRT. However, after iPlan (BrainLAB AG, Feldkirchen, Germany) accepted the Vero4DRT, we were able to conduct the present simulation study.

Here we report the concept and potential benefits of this new irradiation technique with the Vero4DRT by simulating a plan on a radiotherapy treatment planning system for a pancreatic cancer case, and conducting dosimetric comparisons with conventional 2D-DCART and intensity-modulated radiation therapy (IMRT).

MATERIALS AND METHODS

Specs of the Vero4DRT

The concept and configuration of this IGRT system has been introduced previously by Kamino *et al* [4]. Briefly, an X-ray head unit is mounted on the gimbals, and the entire moving unit is installed on an O-ring gantry within a crescent-shaped cover. The X-ray head can rotate along the two orthogonal directions (pan and tilt rotations) up to ± 2.5 degrees, swinging the MV beam up to ± 4.2 cm in each direction from the isocenter on the isocenter plane perpendicular to the beam. In the gimbals tracking mode, this mechanism enables the MV beam to track a target in real time. The swinging motion of the head can be done within the crescent-shaped cover. In addition, the pan and tilt rotations can be independently regulated simultaneously. Therefore, the gimbaled X-ray head unit can track not only linear trajectories but also any complicated trajectories within the mechanical limits. Two imaging units, each consisting of a kilovolt X-ray tube and a flat panel detector, are mounted on the O-ring gantry and provide real-time orthogonal serial radiographs. A gantry-mounted electronic portal imaging device provides information about the MV beam



Fig. 1. External appearance of the Vero4DRT installed in Kyoto University. The X-ray head (indicated by an arrow) can rotate 360 degrees along the inner surface of the O-ring. Here, the O-ring gantry is also rotated around the vertical axis, which enables non-coplanar beam delivery without rotating the couch.

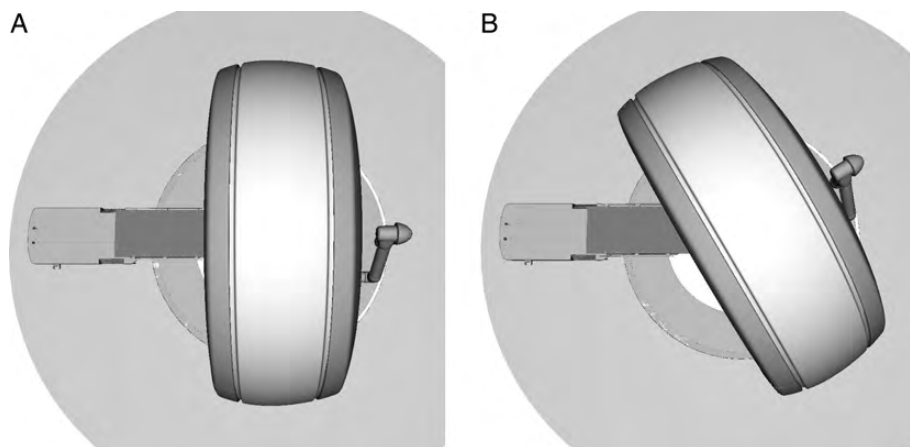


Fig. 2. Look-down views of the Vero4DRT. (A) Rotational angle of the O-ring is 0 (no rotation). (B) Rotational angle of the O-ring is -30° .

shape and position. The maximum field size of the MLC is 15 cm by 15 cm, and the width of the MLCs is 5 mm at the isocenter. The mechanical limit of the O-ring rotating around the vertical axis is ± 60 degrees.

In the present study, because the 3D unicursal irradiation function was not available in the current version of the Vero4DRT, a 3D unicursal plan was simulated by manually creating it on an RTPS (iPlan RT Dose ver. 4.0.0; BrainLAB AG). This simulation was thereafter used to estimate the system's dosimetric advantages by comparing it to other delivery techniques.

Creating collision maps for the Vero4DRT

Due to the rotating nature of these systems, there is a risk of collision between the X-ray head unit or the O-ring and the couch or patient. Because the current version of the iPlan does not support creating 3D unicursal plans, a collision map is mandatory in creating safely deliverable 3D unicursal plans. In this study, we generated collision maps for tumors, such as pancreatic cancers, located in the center of the body. The collision maps were created by setting up both a Rando phantom and a volunteer on the couch top of the Vero4DRT; this allowed the relationships between the rotational angles of the X-ray head unit and the O-ring itself around the vertical axis to be easily understood with respect to the risk of collision. Because collisions of the couch/patients and the O-ring/X-ray head unit are mainly defined by the rotation angles of both the head unit and the O-ring and the extent of the lateral and vertical shift of the couch, we created several collision maps of typical couch positions.

Dosimetric comparisons

A 3D unicursal plan was experimentally created on the iPlan RTPS by manually creating portals for a patient with locally advanced pancreatic cancer clinically treated by IMRT in our department. The prescribed dose was 39 Gy with 2.6 Gy per fraction to the gross tumor volume. The trajectory of the 3D unicursal plan was manually selected to avoid the kidneys as much as possible within the mechanical limits of the system. A 2D-DCART plan was also created based on the same planning CT set for the particular patient. In the 2D-DCART plan, a 360-degree rotational technique was applied. Thereafter, dosimetric comparisons among the 3D unicursal, 2D-DCART, and the clinically applied IMRT plan were performed.

Dose calculations were performed using the radiological path length method with a calculation grid size of 2.5 mm by 2.5 mm. The clinically applied IMRT plan was created with Eclipse ver. 8.5 RTP software (Varian Medical Systems, Palo Alto, CA, USA), with the five-field dynamic MLC method and 15 MV X-ray using a Clinac iX (Varian Medical Systems, Palo Alto, CA, USA). Dose calculations were conducted using the pencil beam convolution algorithm with a Batho power-law correction. The calculation

grid size was 2.5 mm by 2.5 mm. The MLC width of the Clinac iX was 5 mm at the isocenter, which is the same width as the Vero4DRT.

RESULTS

Collision maps for the Vero4DRT

A collision map of the most typical couch-top position for patients with pancreatic cancer, in which the tumor is located in the center of the body, is indicated in Fig. 3. According to this map, there is no risk of collision, even if the head unit is rotated within the O-ring at any angle, as long as the rotating ring is within ± 27 degrees around the vertical axis of the O-ring. However, collisions are expected in specific gantry angles if the ring rotates more than 27 degrees, as indicated by the shaded area in Fig. 3.

Dosimetric comparisons

A 3D unicursal plan was successfully simulated on iPlan RT Dose ver. 4.0.0. A projection map using the iPlan for the 3D unicursal plan is shown in Fig. 4. This indicates that both the X-ray head and the O-ring simultaneously rotate and avoid the kidneys as much as possible, within the mechanical limits of the Vero4DRT. Doses in the 3D unicursal plan were at least comparable to or even improved over those from 2D-DCART and IMRT with respect to both the target and organs at risk. (Figs 5 and 6) The doses covering 95% of the planning target volumes for the 3D unicursal, 2D-DCART and IMRT plans were 95.5%, 95.8% and 97.0%, respectively. For the 3D unicursal, 2D-DCART and IMRT plans, the V20% values were 11.5%,

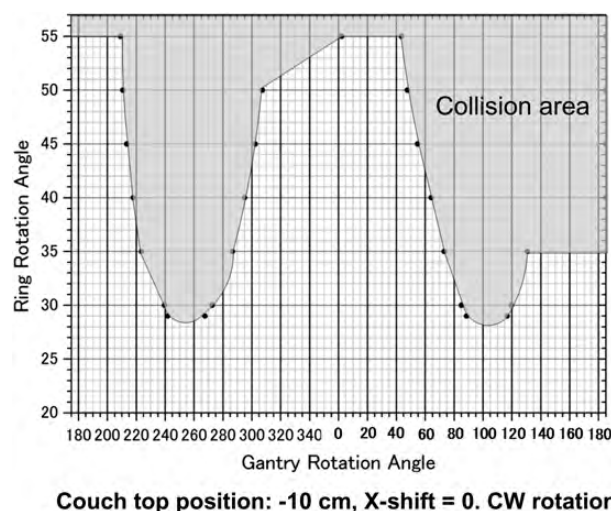


Fig. 3. A collision map under the following conditions: couch top position of -10 cm, X-shift = 0. CW rotation, which assumed treatment of patients with pancreatic cancer.

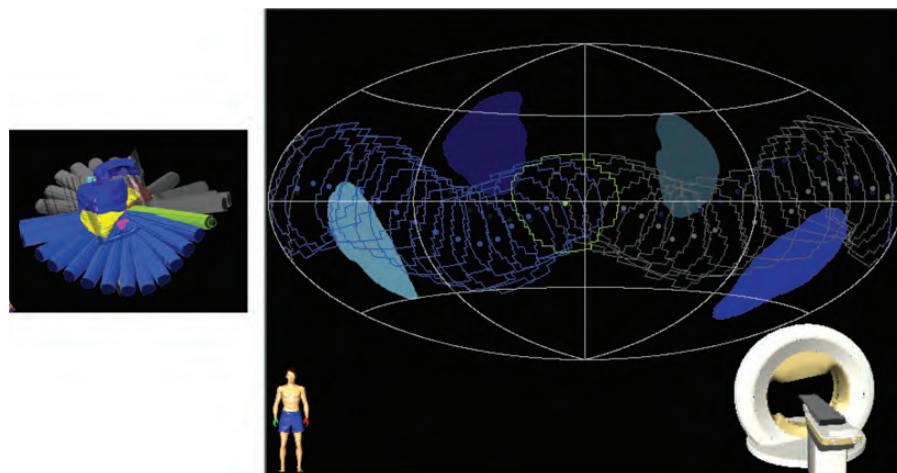


Fig. 4. A beam projection map for the three-dimensional unicursal plan on iPlan ver. 4.0.0. The transverse axis indicates the rotation angle of the gantry head unit, whereas the vertical axis represents the rotation angle of the O-ring. Projected right and left kidneys (total of four projections) are indicated on the map. In this plan, we tried to avoid both kidneys as much as possible within the mechanical limits of the Vero4DRT.

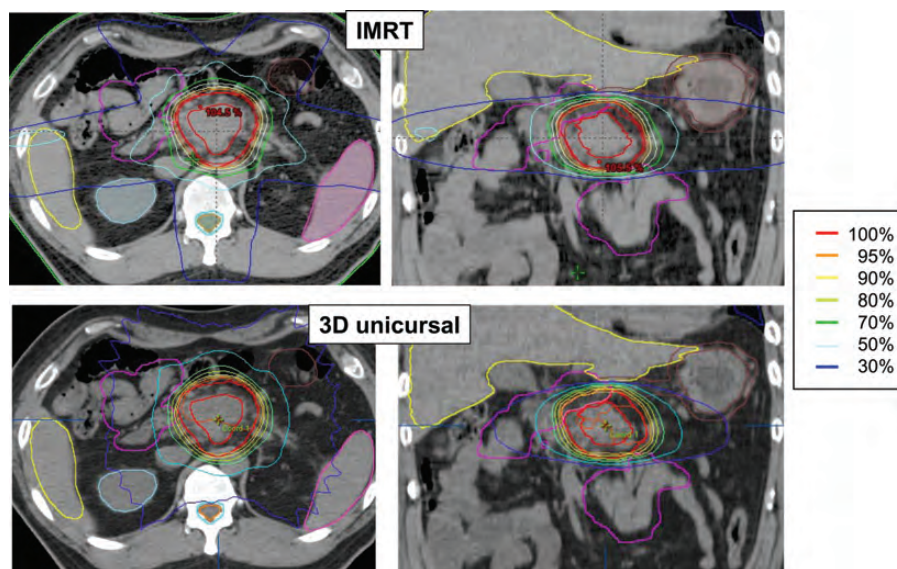


Fig. 5. Comparison of dose distributions between intensity-modulated radiation therapy and the three-dimensional unicursal plan.

31.3% and 9.4%, respectively, for the right kidney, and 9.6%, 27.8% and 14.4%, respectively for the left kidney; the V90% values were 4.7%, 4.3% and 3.2%, respectively, for the small intestine, and 3.6%, 4.1% and 3.2%, respectively, for the stomach; and the V30% values were 6.0%, 0.5% and 24.7%, respectively, for the spinal cord.

Comparison of monitor units

The estimated monitor unit (MU) required for the 3D unicursal plan to deliver 2.6 Gy was 477 MU, which was only 7% higher than the MU for 2D-DCART plan (446 MU) and 22.1% lower than that for the IMRT plan (612 MU).

DISCUSSION

Although one of the special features of the Vero4DRT is the tracking irradiation function utilizing the gimbaled X-ray head [5], this system has additional advantages over conventional linear accelerators that originate from its unique configuration. The all-in-one IGRT design, the high mechanical accuracies, and the orthogonally installed kV imaging systems lead to further benefits. These features were realized by the unique O-ring design.

In this study, we confined our attention to another unique feature: the system's ability to deliver non-coplanar

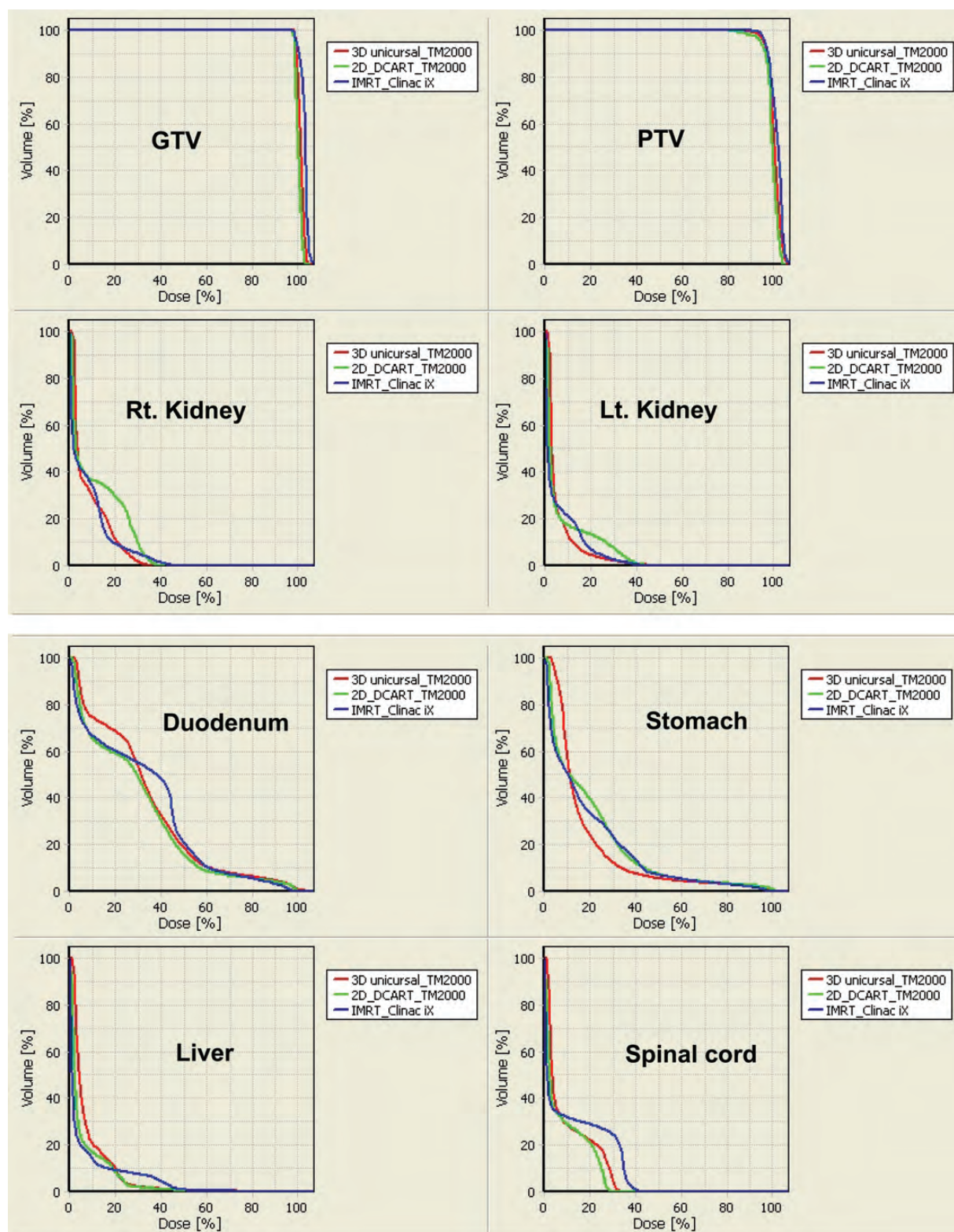


Fig. 6. Comparison of dose–volume histograms among three-dimensional (3D) unicursal, two-dimensionally rotational dynamic conformal arc irradiation, and intensity-modulated radiation therapy plans regarding gross tumor volume (GTV), planning target volume (PTV), right kidney, left kidney, duodenum, stomach, liver and spinal cord. In this case, dose–volume data of the 3D unicursal plan was at least comparable to those for other radiation techniques for both targets and organs at risk.

beams without rotating the couch, which is possible because of the ingenious O-ring design. (Figs 1 and 2) This specific feature allows very high throughput when treating patients with non-coplanar beams under image guidance. This is especially useful in stereotactic irradiation where non-coplanar beams are essential; because the couch must be manually rotated, it takes a significantly longer time to deliver non-coplanar beams using conventional linear accelerators [11]. In fact, on a routine clinical basis, we currently complete one session of stereotactic body radiation therapy for patients with lung cancer—treatment with four to five non-coplanar beams and two coplanar beams—within 25 min using the Vero4DRT under both kV X-ray and cone-beam computed tomography guidance.

We are also conducting a dose-escalation study in locally advanced pancreatic cancer with the IMRT technique. We have found that IMRT is very useful in escalating the dose to the pancreatic tumor as well as in keeping the doses to the surrounding organs, such as the duodenum and the stomach, lower than the tolerance dose. However, because movements of the upper abdominal organs such as the pancreas are associated with respiration effects, we decided to apply IMRT under breath-holding conditions. The drawbacks of the breath-holding IMRT technique are higher MU values and longer treatment time compared to conventional beam delivery methods.

In the present estimation, it is expected that 3D unicursal irradiation techniques give an almost comparable dose distribution compared to IMRT, whereas the MUs of 3D unicursal plans would be significantly lower than those for the IMRT plans. In addition, the beam delivery times can be considerably shorter than those of IMRT. Therefore, the 3D unicursal RT technique is promising in this field. Also, the 3D unicursal plan is expected to improve dose distributions and shorten treatment times in stereotactic irradiation of brain and body lesions because continuous non-coplanar irradiation can be achieved while avoiding organs at risk, without couch rotation.

A similar irradiation technique was reported by Yang *et al.* with traditional accelerators in volumetric modulated arc therapy, in which couch and gantry simultaneously rotate during irradiation [12]. This technique can realize similar beam trajectories to those realized by 3D unicursal irradiation with the Vero4DRT. However, safety and amenity of patients associated with the couch rotation would be an issue in the clinical applications of the above-referenced technique.

On the other hand, 3D unicursal irradiation with the Vero4DRT is expected to be a safe and comfortable treatment because the couch is fixed during irradiation. In addition, the Vero4DRT has both software and hardware safety features in order to protect patients from any collisions with the gantry. In the software approach, the system has safety range data for gantry angle, ring angle and couch position, respectively.

Therefore, without any additional intervention by an operator, the system automatically avoids any positions outside the safety range. In the hardware approach, the Vero4DRT is equipped with a touch-sensitive safety switch for immediate motion stop in case of collision. The switch is installed on the gantry front cover where potential collision risk is recognized. With those specific features, the Vero4DRT can safely be operated in daily clinical applications.

There are some limitations to applying this technique in clinics. First, the current version of the Vero4DRT does not allow simultaneous rotation of both the X-ray head unit and the O-ring itself. Therefore, additional developments of the hardware and software are necessary to realize this new technique, as well as further improvements in the iPlan software. Second, there are some mechanical limitations. For safety reasons, the rotational speed is limited by Japanese Industrial Standards to 7 degrees per second for gantry head rotation and 3 degrees per second for ring rotation. These limitations should be included in the development of the software for 3D unicursal irradiation. The current study only used a manual simulation of the irradiation to estimate the potential dosimetric advantages of the 3D unicursal irradiation technique. It took a few hours to create the 3D unicursal plan manually, and the plan was not optimized by a computer program. Therefore, we believe that this kind of study will need to be repeated once hardware and software developments are completed to allow future comparison studies that confirm the expected advantages of 3D unicursal plans for specific conditions and sites.

In conclusion, the 3D unicursal irradiation technique with the Vero4DRT will have the following potential: improvement of dose distribution compared to the 2D-DCART technique, shorter treatment time compared to conventional 3D conformal radiation therapy/IMRT, and lower monitor units compared to IMRT. These potential advantages need to be validated after the development of a compliant version with 3D unicursal RT function for each specific situation.

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CONFLICT OF INTEREST

T.M., M.K. and M.H. have an advisory contract with Mitsubishi Heavy Industries. M.K. and M.H. have a

research contract with Mitsubishi Heavy Industries. K.N. is an employee of Mitsubishi Heavy Industries.

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